Mechanisms for Amplification of fusion Reaction Rates in Solids (MARRS)

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MARRS Overview

Program Objective:
Demonstrate fusion rate amplification in solids

Increase rates from ~0.1 (state-of-the-art) to 10^6 fusion reactions/second/gram with predictive models

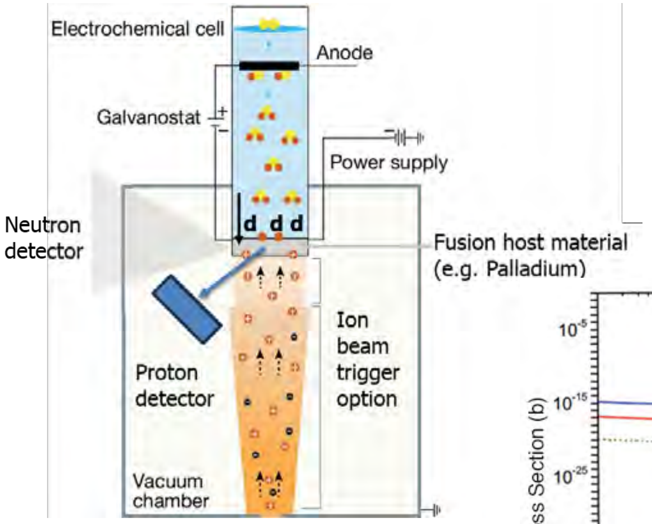
Vision:
Harvest energy from fusion in solids to supply modular power for National Security applications

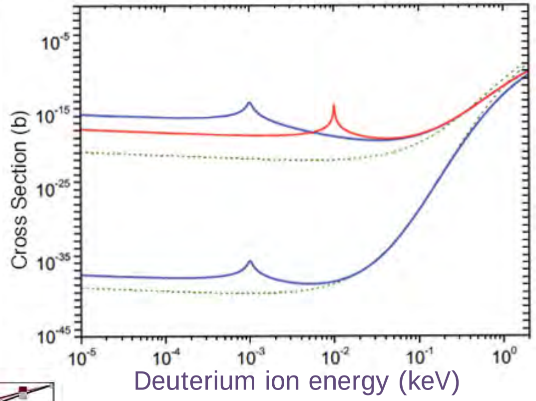
MARRS – build on recent advances

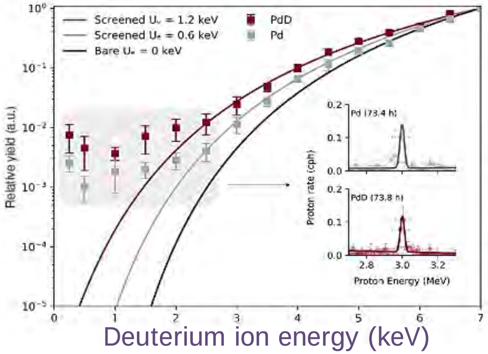
1. Sensitive, reproducible **Measurements** of particle emission from fusion reactions in solids

2. Initial **Theory** on fusion rate enhancements in solids

3. Initial **Data** on fusion rate enhancements in solids

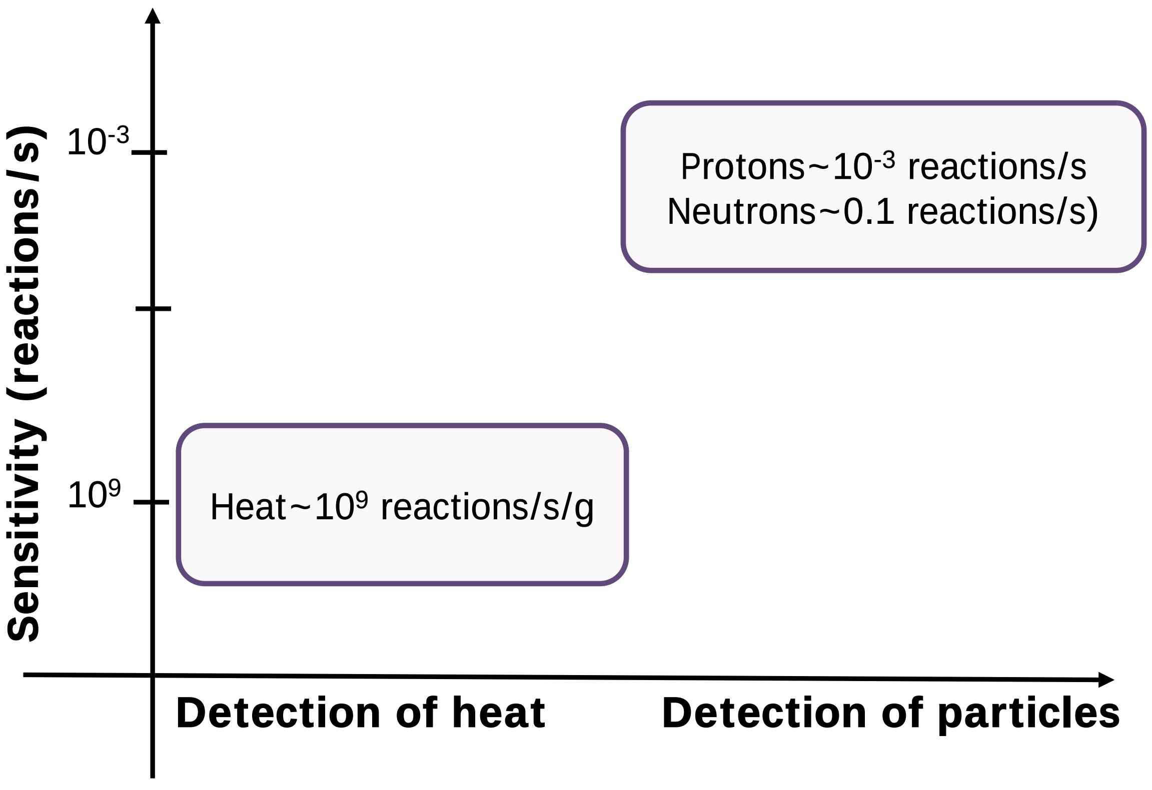




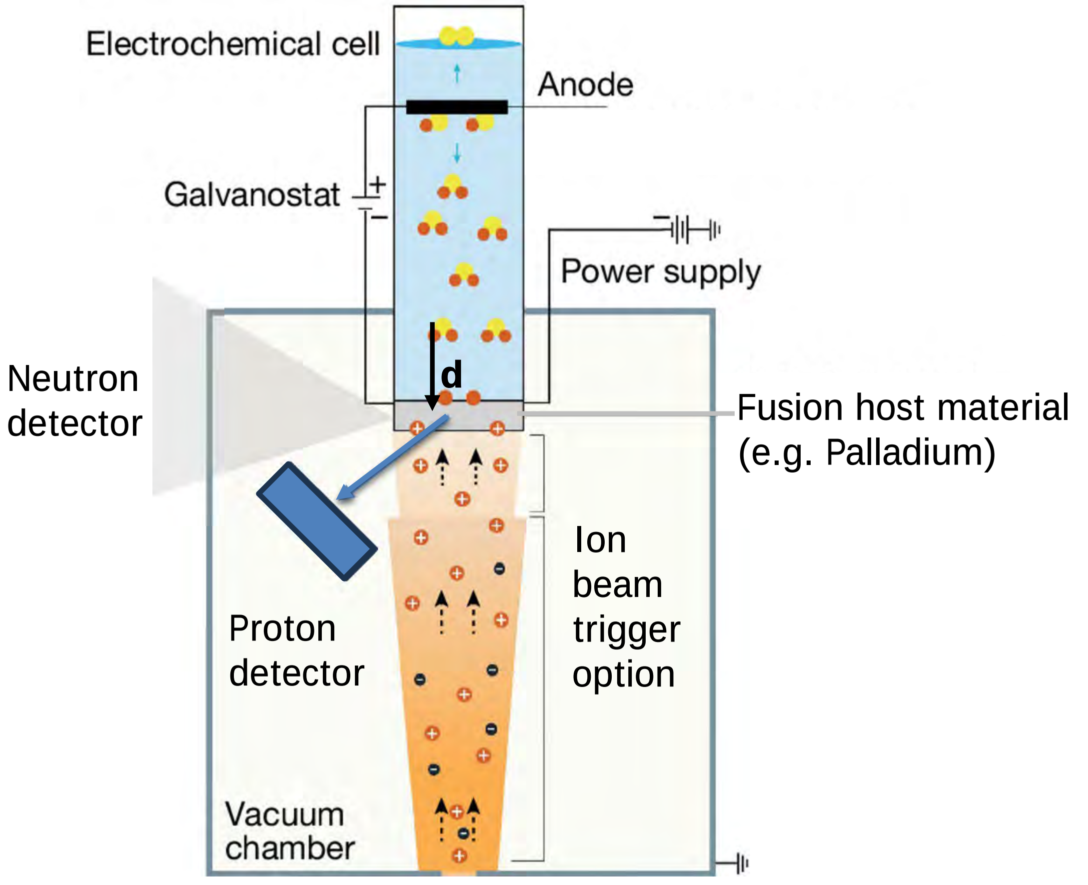


Czerski, “Deuteron-deuteron nuclear reactions at extremely low energies”, Phys. Rev. C 106, L011601 (2022); arxiv:2409.02112v1
Chen et al., “Electrochemical loading enhances deuterium fusion rates in a metal target”, Nature 644, 640 (2025)
Karahadian, et al. https://doi.org/10.2172/2569797 (2025)
ARPA-E LENR program

Particle detection is more sensitive than heat detection



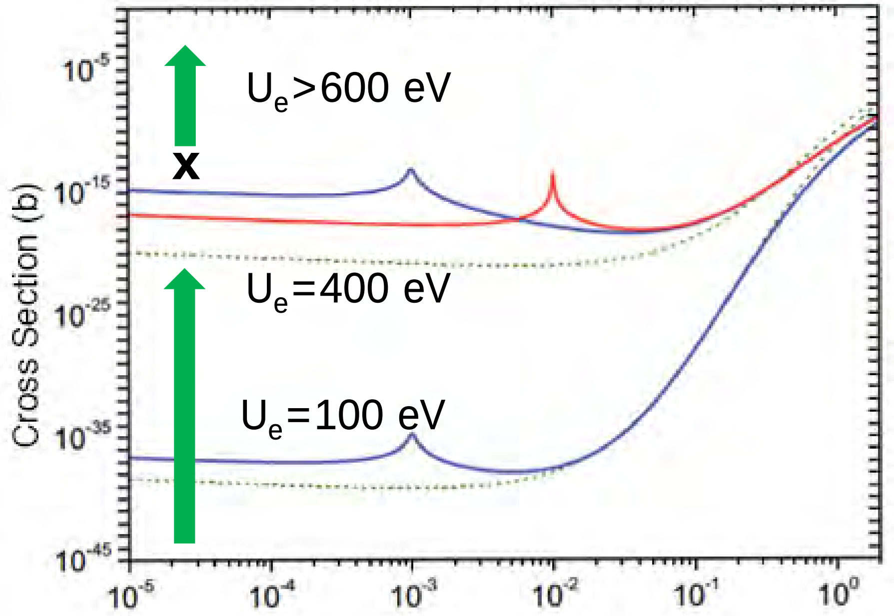
- d+d → n+^{3}He, t+^{1}H (3.5 MeV), 1 Watt~10^{12} reactions/second



Chen, et al. Nature 644, 640 (2025); Karahadian, et al., https://doi.org/10.2172/2569797 (2025); Schenkel, Fork, Trevithick , Berlinguette, et al., US20210151206A1

New theory and data on fusion reaction rates in solids

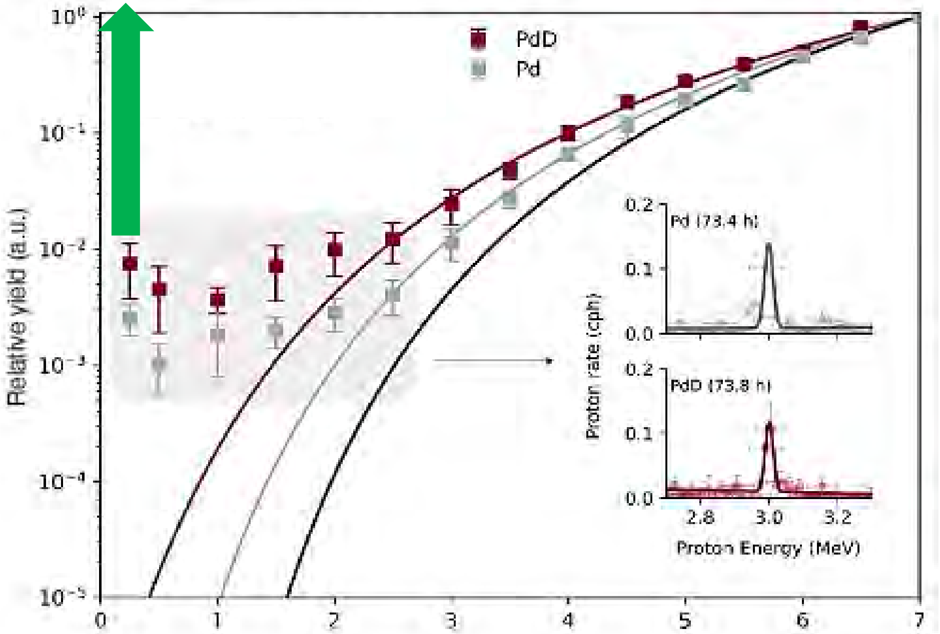
Theory



Deuterium ion energy (keV)

Non-resonant (dotted) and resonant (solid) cross sections for U_e = 400 eV (upper) and U_e = 100 eV (lower). Blue: resonance energy of 1 eV, red: 10 eV. Prediction of ≥1 Watt/gram for 10^{-13} barn in "properly loaded metal".

Experiment



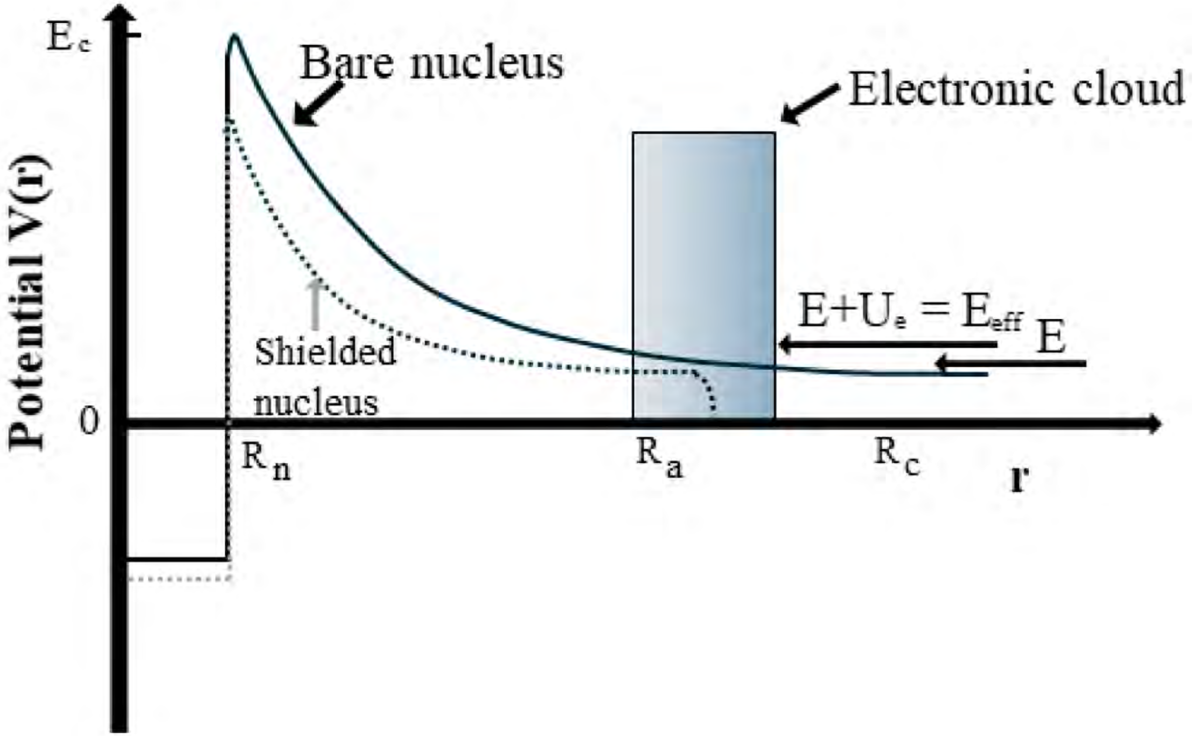
Deuterium ion energy (keV)

Deuterium-deuterium fusion yield as a function of ion beam trigger energy in palladium. The fusion yield near room temperature corresponds to a cross section of ~$2\text{x}10^{-13}$ barn.

MARRS will quantify fundamental mechanisms and optimize conditions to amplify fusion rates

Czerski, Phys. Rev. C 106, L011601 (2022); arxiv:2409.02112v1; Karahadian, et al. https://doi.org/10.2172/2569797 (2025); Metzler et al., 2024, New J. Phys. 26, 101202

MARRS will exploit new insights to amplify fusion reaction rates in solids



Fusion rate ~ N² <σ v>

Factors to amplify fusion reaction rates in solids:

U_e → electron screening
N → deuterium loading
v → deuterium velocity

$$\sigma_f(E, U_e) = \frac{1}{\sqrt{E(E+U_e)}} e^{-\sqrt{E_g/(E+U_e)}} S(E)$$

Interplay of nuclear, quantum, and materials science - limited quantitative understanding to date.

Assenbaum (1987), adapted from Lipoglavšek

Mechanisms to amplify fusion reaction rates in solids

Fusion Rate Amplification Factors

Host Materials U_e

- Electron screening $U_e \geq 600$ eV
- Metal hydrides
- Alloys, MOFs
- Vacancies
- ...

Fuel Loading N

- MeD_x, $x \geq 1$
- Electrochemistry
- Gas phase
- Fuel mobility
- ...

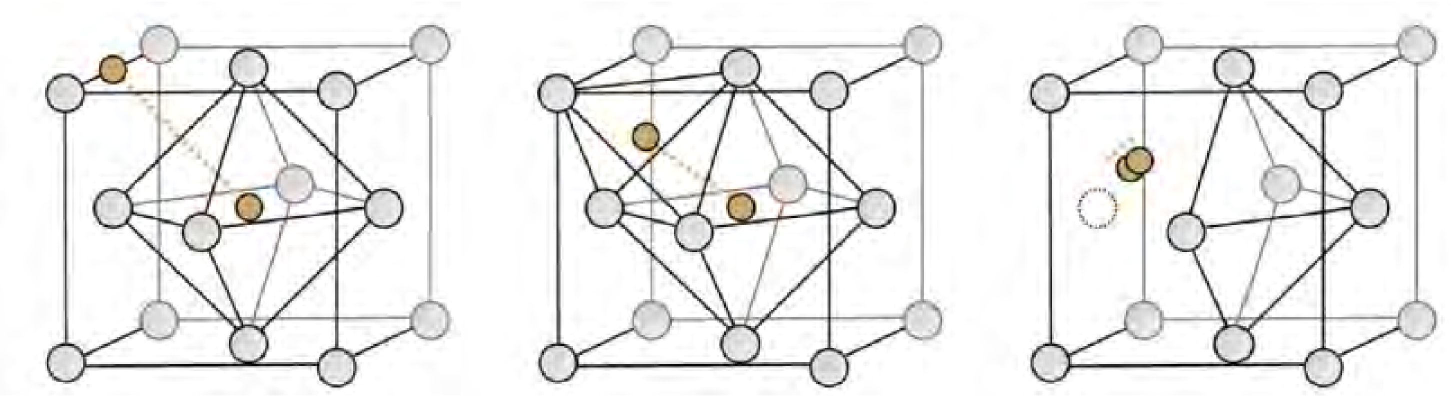
Fusion Triggers ν

- Lattice excitations
- Electronic excitation
- Coherent excitations
- Phonons, photons
- ...

Mechanisms that underpin fusion reactions in solids will be combined and optimized for reproducible reaction rate amplification with control knobs

Amplification factors: Host materials

Metal hydride engineering



Configurations of deuterium atoms in the palladium lattice. Right: a deuterium pair trapped in a vacancy. We can tap into hydrogen storage science.

U_e → increased electron screening from the electronic structure of d-d pairs trapped in vacancies

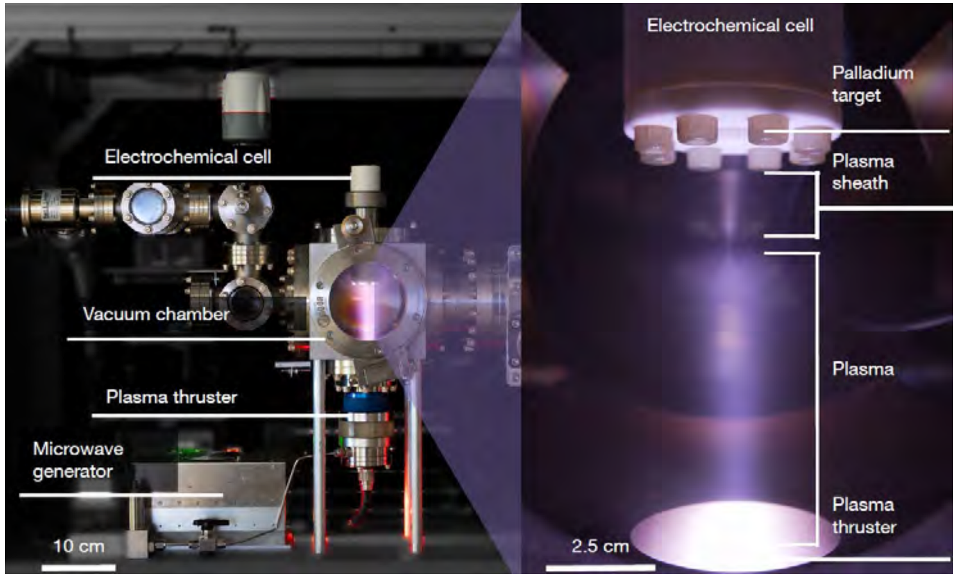
N: density of deuterium, v: deuterium velocity,
σ: cross-section; E_g: Gamow factor, E: reaction energy,
U_e: electron screening potential

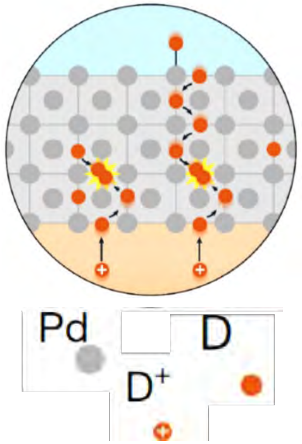
Evidence that vacancy engineering of metal hydrides can amplify fusion rates

Metzler et al., 2024, New J. Phys. 26, 101202

Amplification factors: Fuel loading

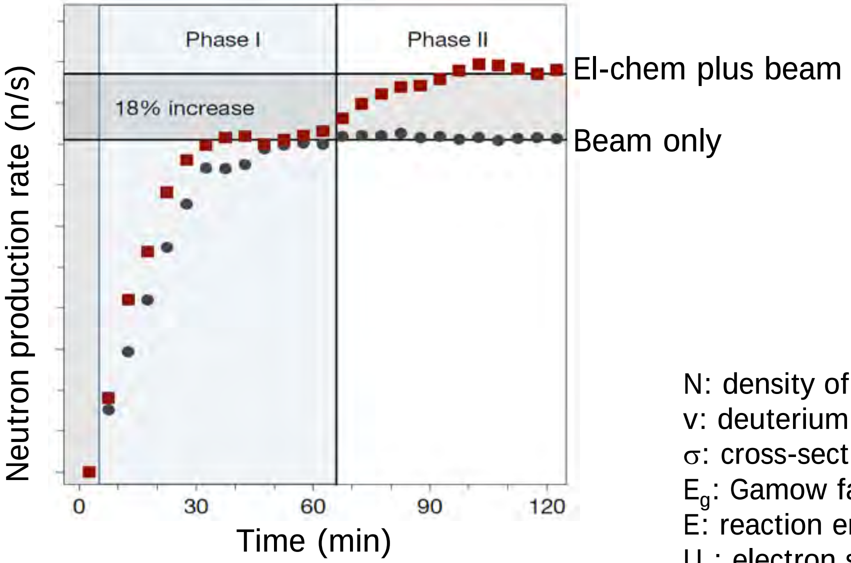
Data on control of fusion by fuel loading with electrochemistry





A membrane reactor integrated with a vacuum chamber. Demonstration fusion rate increases due to electro-chemical fuel loading in a beam driven fusion experiment (15 keV).

N → increase the density of mobile deuterium in MeD_x, x≥1



N: density of deuterium,
v: deuterium velocity,
σ: cross-section;
E_g: Gamow factor,
E: reaction energy,
U_e: electron screening potential

Evidence that deuterium fuel loading into metal hydrides can amplify fusion reaction rates

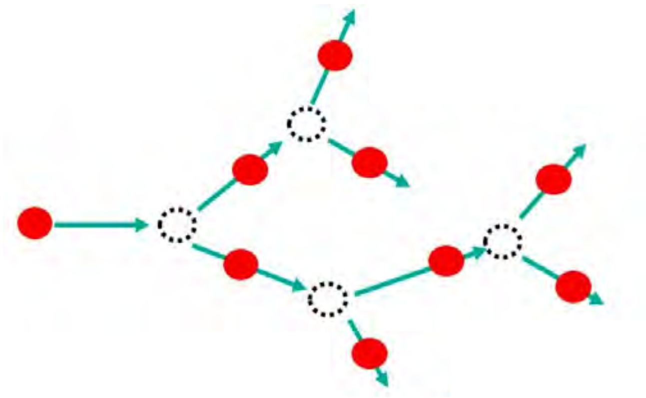
MeD: Metal Deuterium

Chen, et al. Nature 644, 640 (2025)

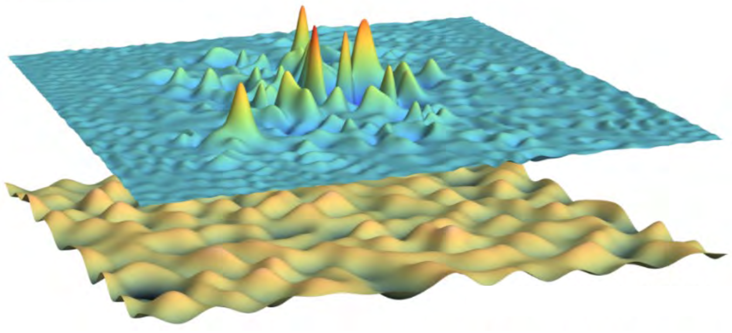
Amplification factors: Fusion triggers

Triggers stimulate fusion reactions

Visualizations of Trigger Events



Collision cascade with energetic deuterium knock-on atoms and formation of vacancies



Coupled **dynamics of charge carriers and lattice vibrations** from a trigger pulse of coherent electronic excitations

v → increase the velocity of deuterium atoms by momentum and energy transfer with photons or particles

N: density of deuterium,
v: deuterium velocity,
σ: cross-section;
E_g: Gamow factor,
E: reaction energy,
U_e: electron screening potential

Provide just the right "spark" to ignite and amplify fusion reactions efficiently

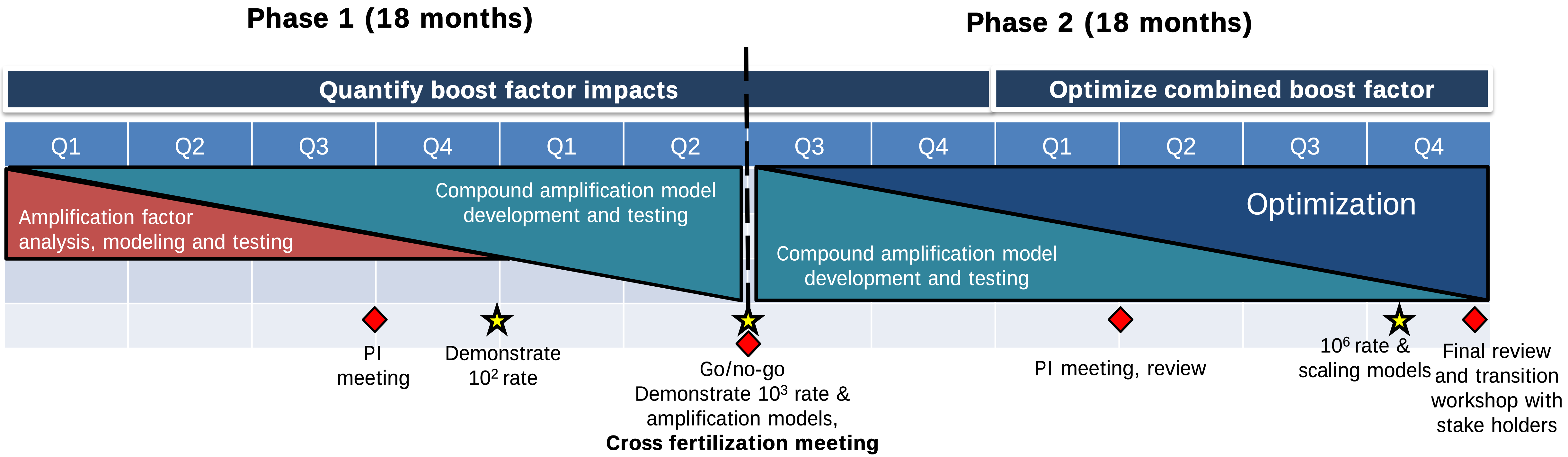
Aydin, et al, *Proc. Natl. Acad. Sci.* 121, e2404853121 (2024)

Program Metrics

Metric	Units	SOA	Phase 1	Phase 2
Fusion rate	Reactions/s/g	~10^{-1}	10^3: Quantify cumulative amplification effects	10^6 : Reliable, reproducible
Quantitative understanding		Nascent	Develop quantitative, predictive models for rate amplification	Refine predictive models towards power production

- At the end of the program, we will be able to quantify mechanisms for scaling to 10^6 reactions/s/g and beyond

Program Structure



- Teams from universities, industry and National Labs
- Teams with capabilities in materials, fuel loading and triggering, supported by modeling, exploring sets of combined amplification factors

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